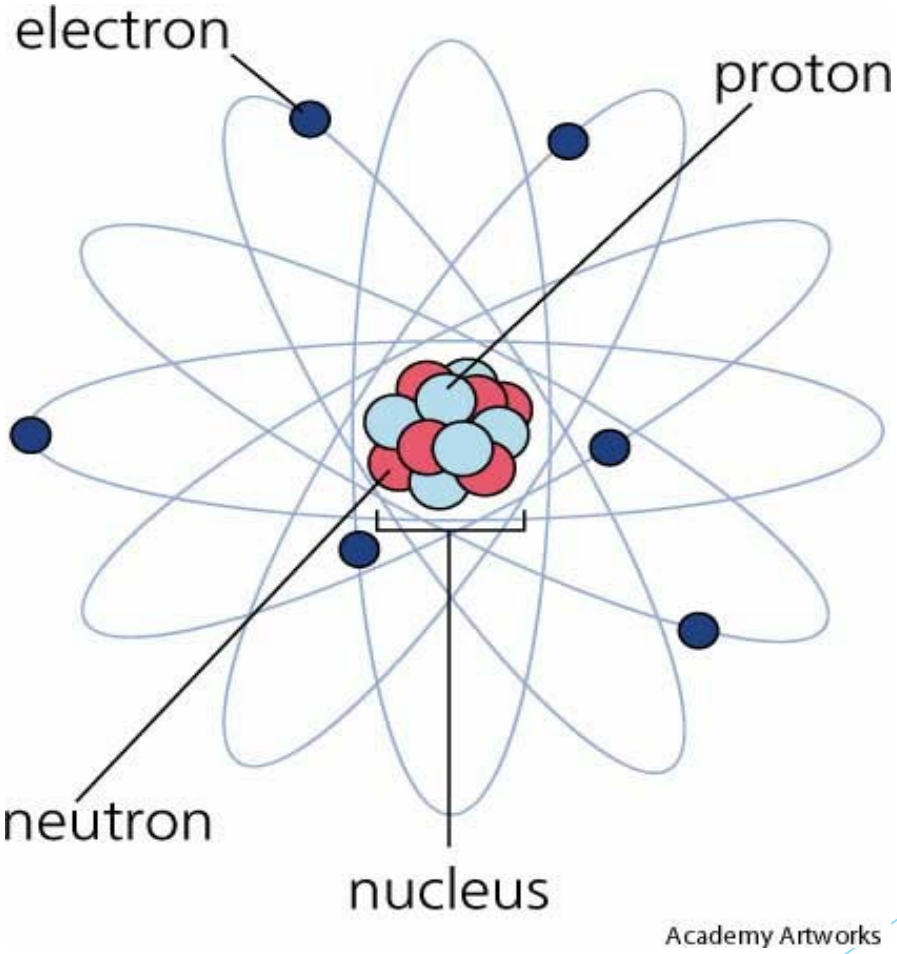
Matter, Atoms, and Quarks

Jeffrey A. Mahn
Nuclear Engineer (Retired)
Albuquerque, NM USA
jamahn47@gmail.com

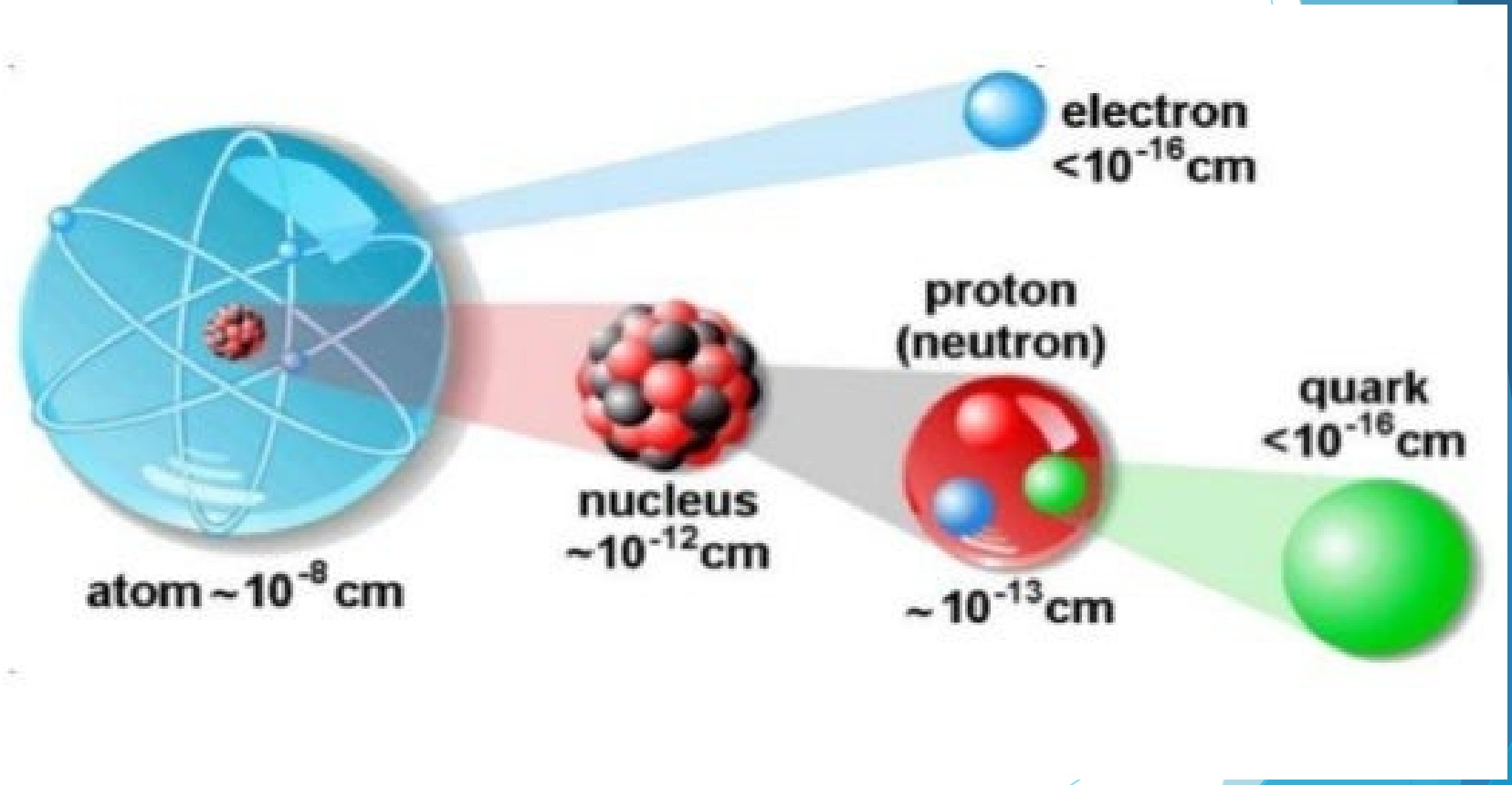
Makeup of Our World

- Matter – the world we can see, touch, hear, smell, and taste
- Atom – the building block of matter
- Quark – elementary particle and fundamental constituent of matter

The Atom



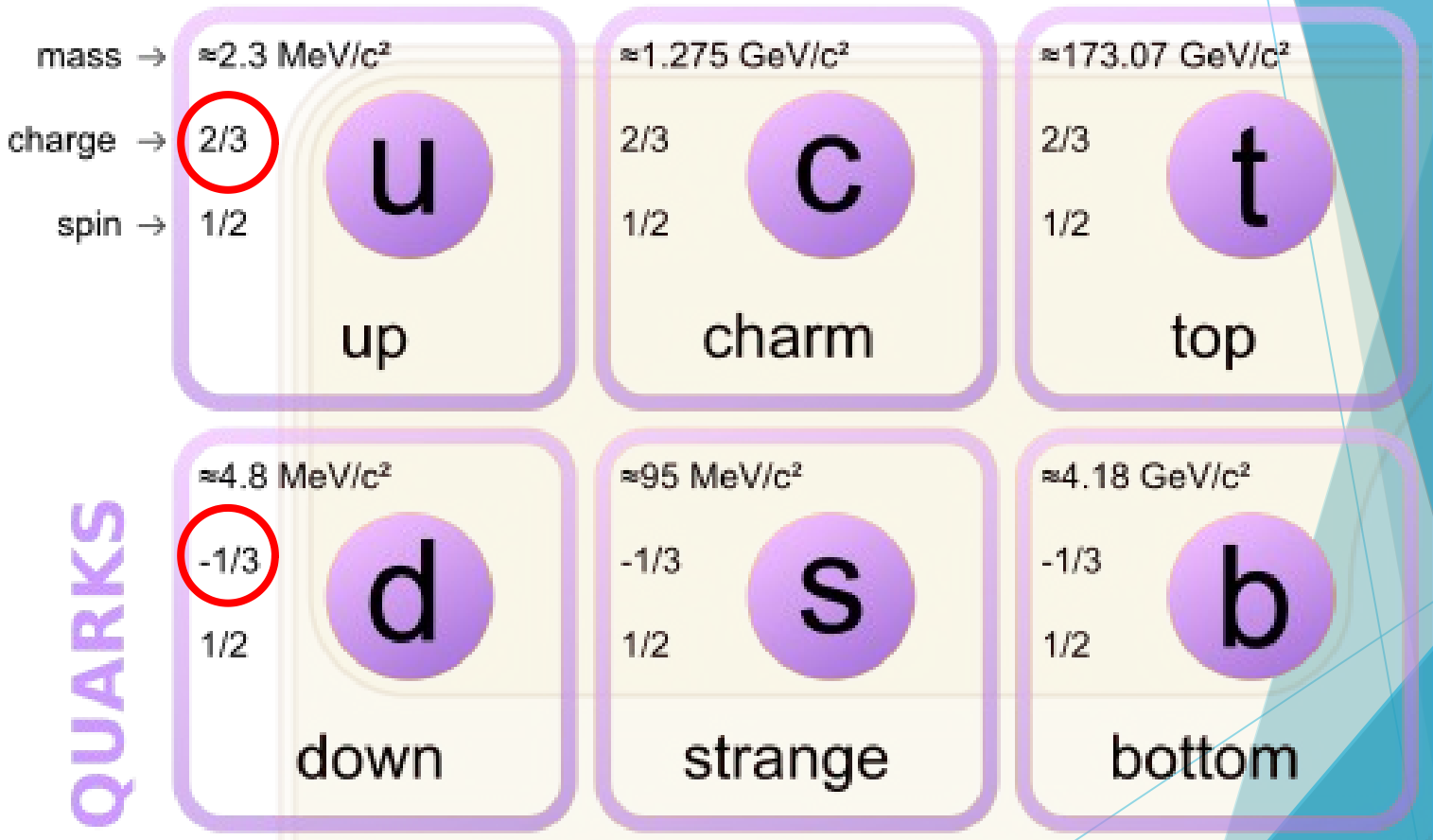
Atomic Structure



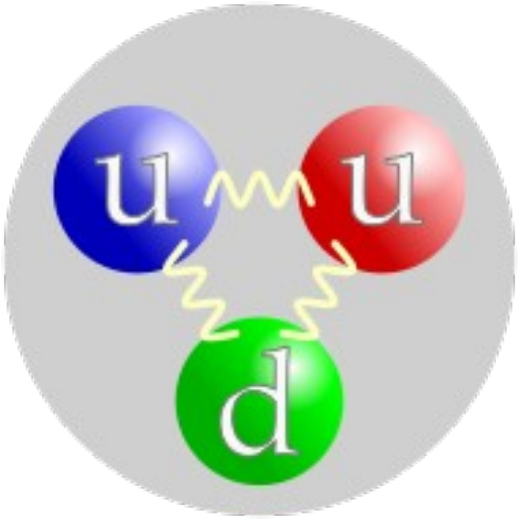
Quarks

- Six kinds of quarks called up, down, charm, strange, top, and bottom
- Combine to form composite particles called hadrons, most stable of which are protons and neutrons
- Only up and down quarks occur commonly in nature

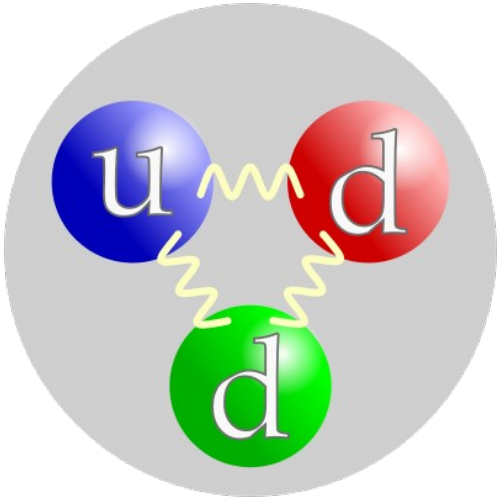
Quark Properties



Proton and Neutron Structure

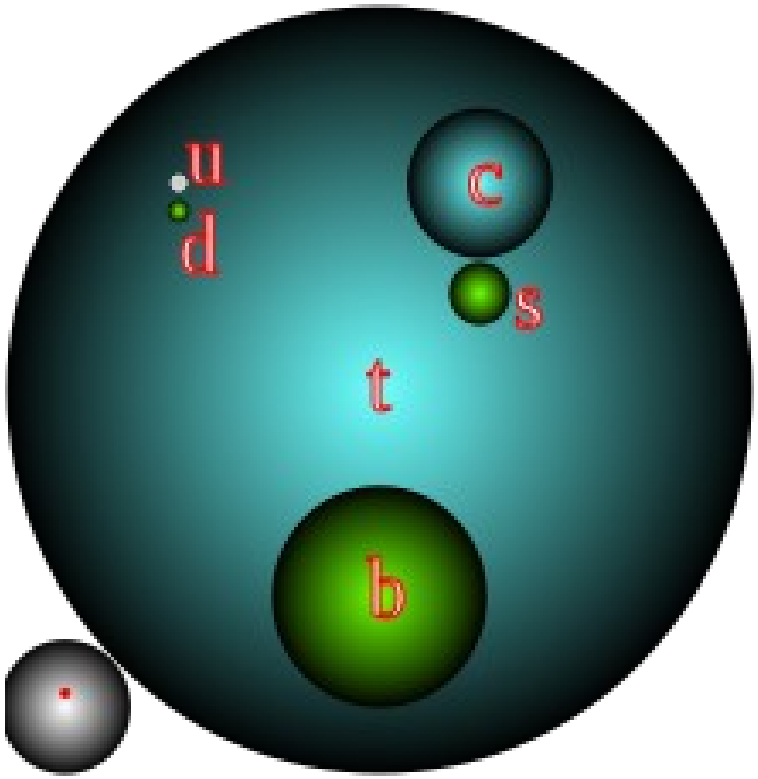


Proton composed of two up quarks and one down quark that result in +1 electric charge



Neutron composed of one up quark and two down quarks that result in no net electric charge

Relative Quark Masses



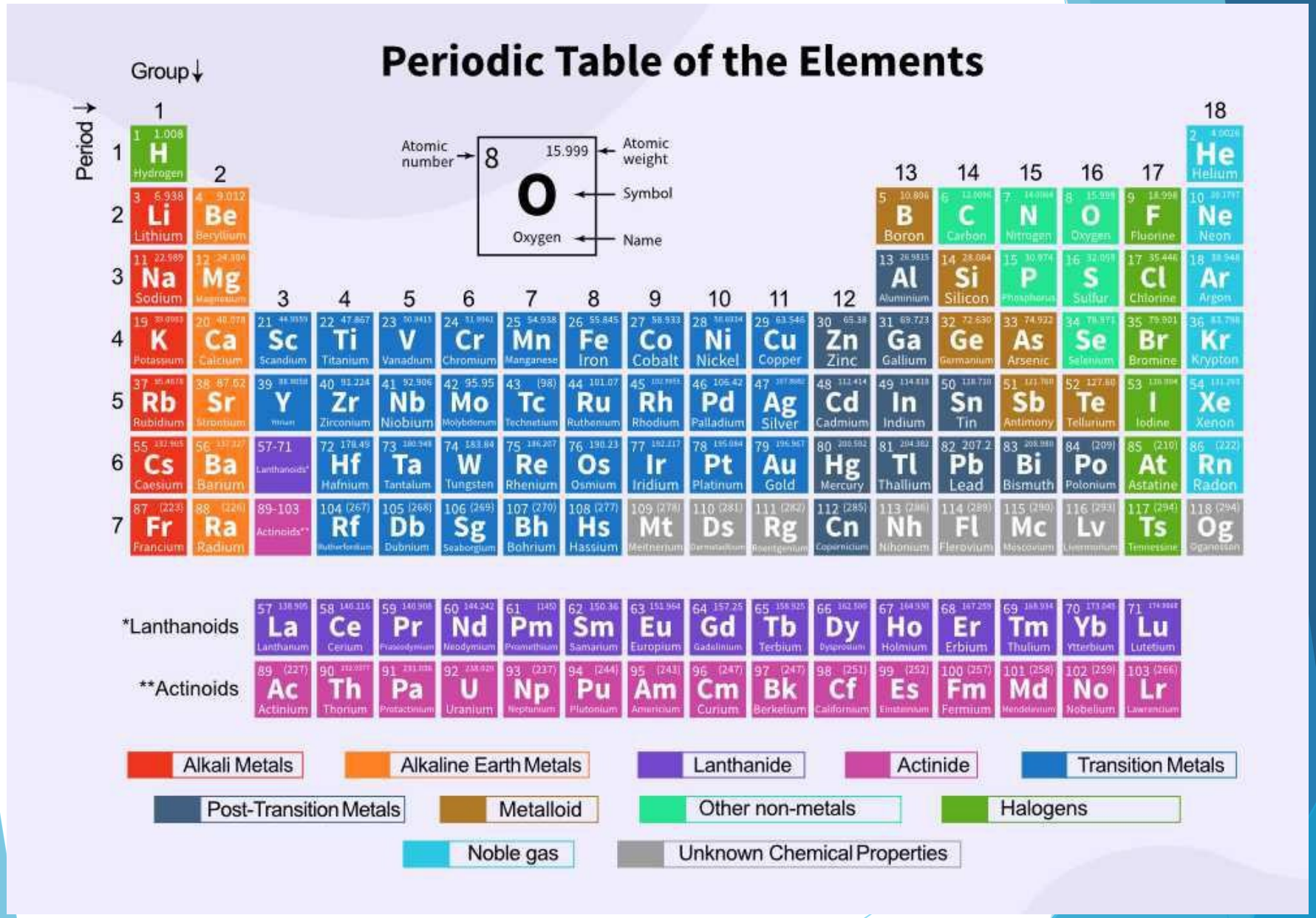
Relative masses for all six quarks, illustrated as balls of proportional volumes.

Proton (gray) and electron (red) are shown in bottom left corner for scale.

Chemical Elements

Chemical Elements

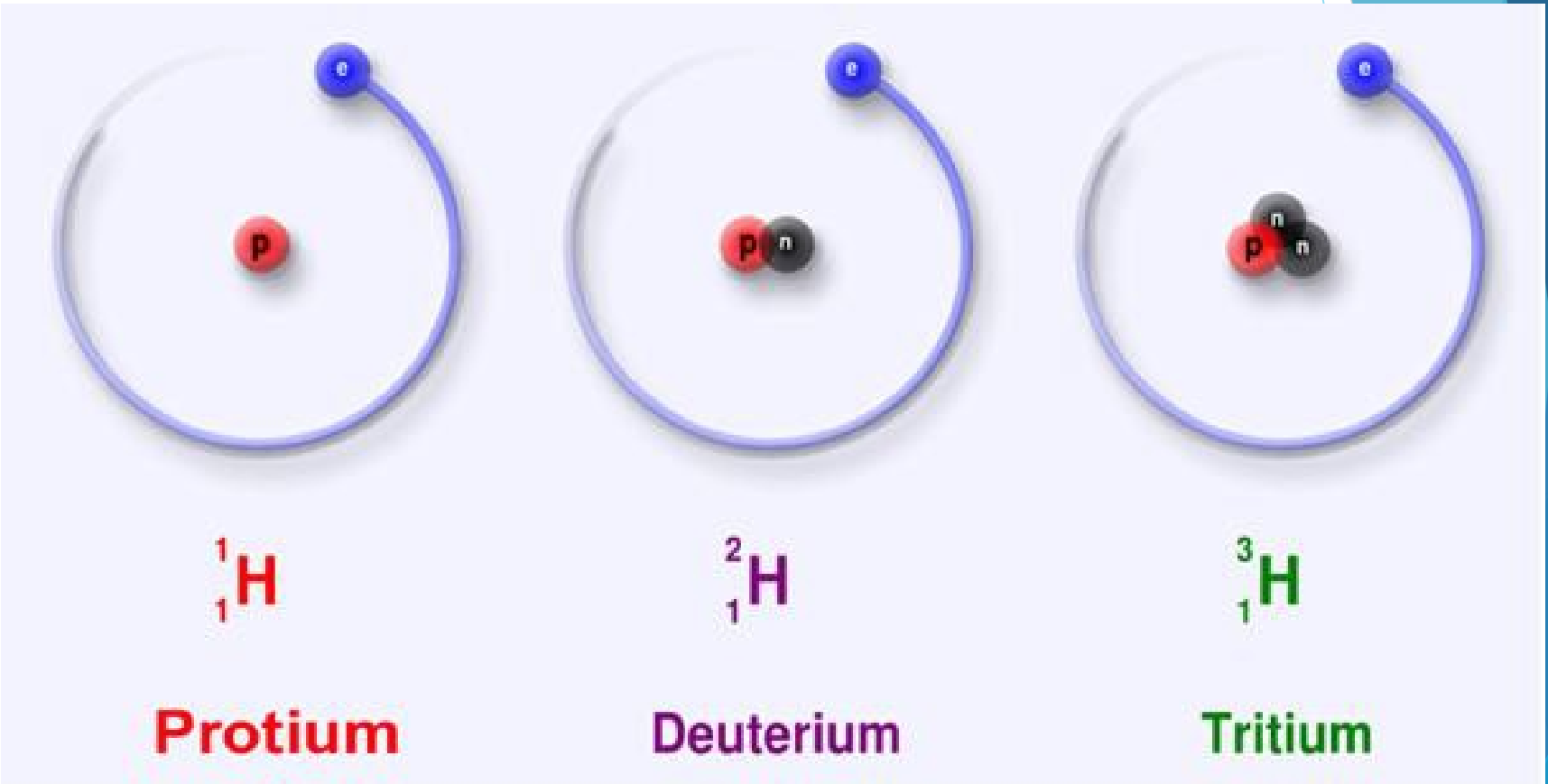
- Characterized by number of protons (atomic number) in atomic nucleus
- Periodic Table of the Elements - known elements arranged in order of ascending atomic number (number of protons) in atomic nucleus
- 118 known elements
  - All elements above uranium (atomic number 92) manmade


Periodic Table of the Elements
Group
Period
Atomic number
Atomic weight
Symbol
Name
8
15.999
O
Oxygen
*Lanthanoids
**Actinoids
Alkali Metals
Alkaline Earth Metals
Lanthanide
Actinide
Transition Metals
Post-Transition Metals
Metalloid
Other non-metals
Halogens
Noble gas
Unknown Chemical Properties

Isotope

- Isotopes of chemical element contain same number of protons, but different number of neutrons in atomic nucleus
- Isotope nucleus may be stable or unstable (radioactive)
- All chemical elements consist of multiple isotopes
  - Element atomic mass is weighted average (% abundance) of stable isotope masses
  - Atomic mass for elements with no stable isotopes is mass of longest-lived radioactive isotope (generally in parentheses)
- Over 3,000 chemical isotopes identified

Isotopes of Hydrogen



Stable Isotopes of Carbon

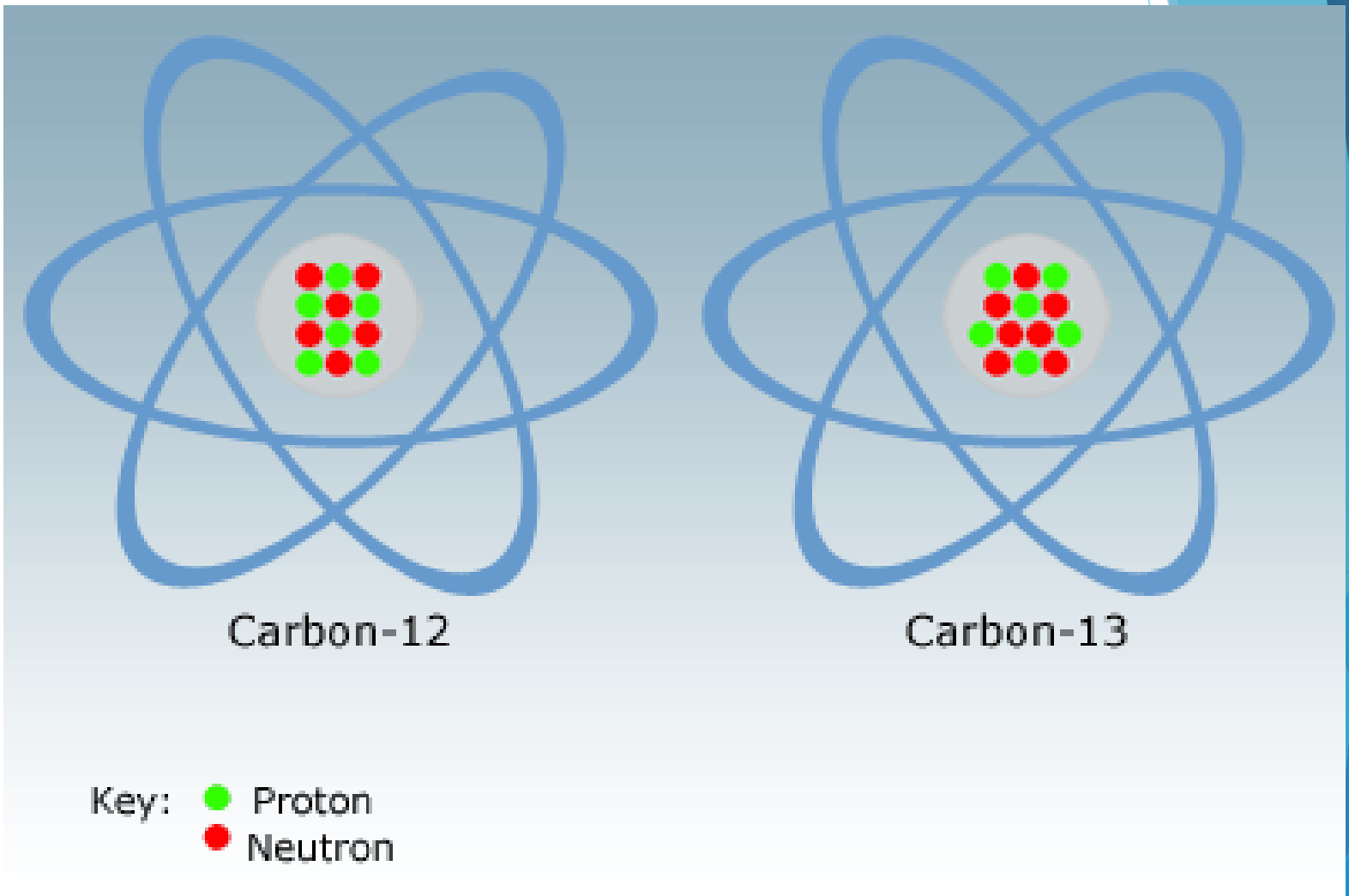
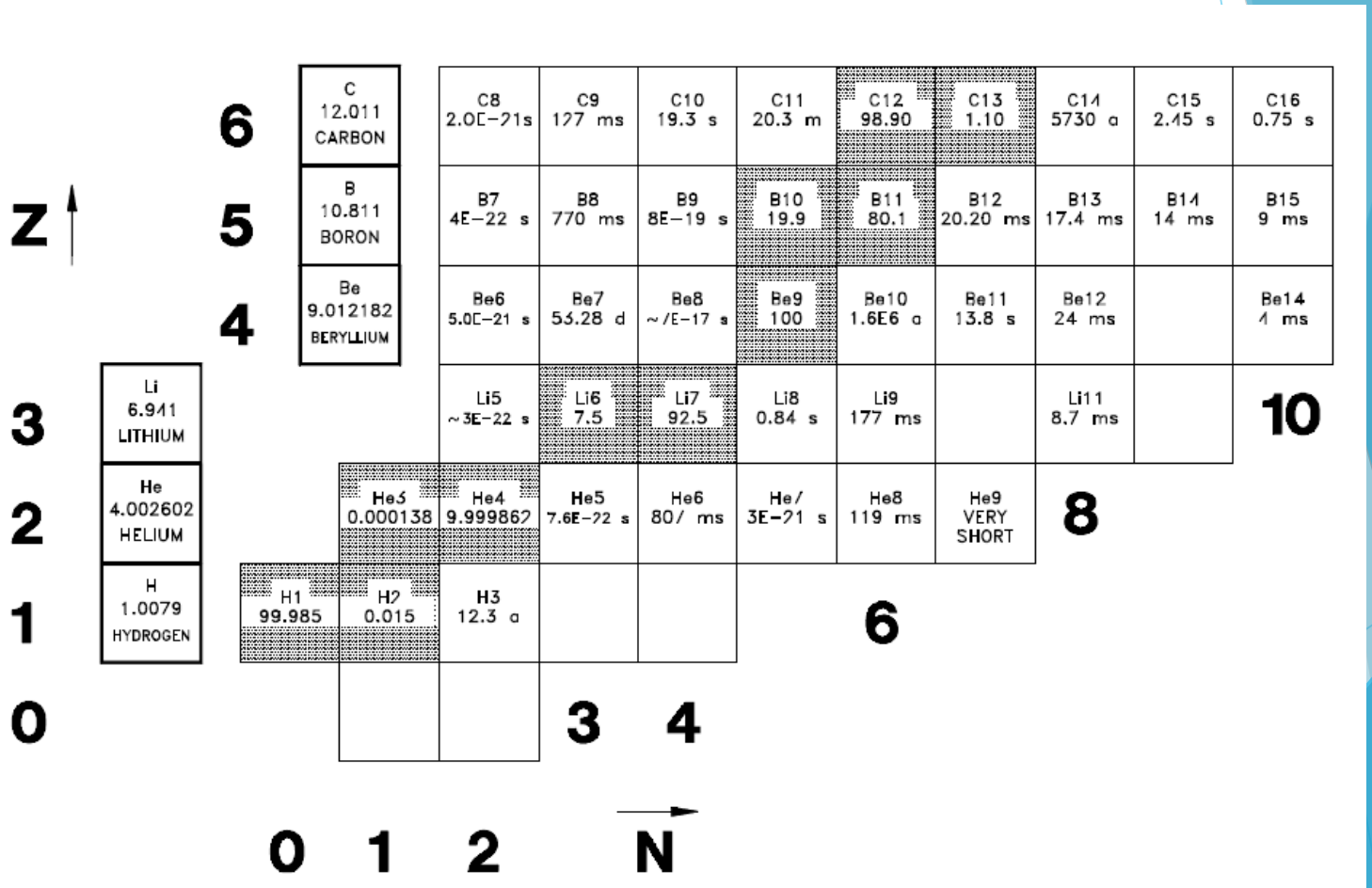


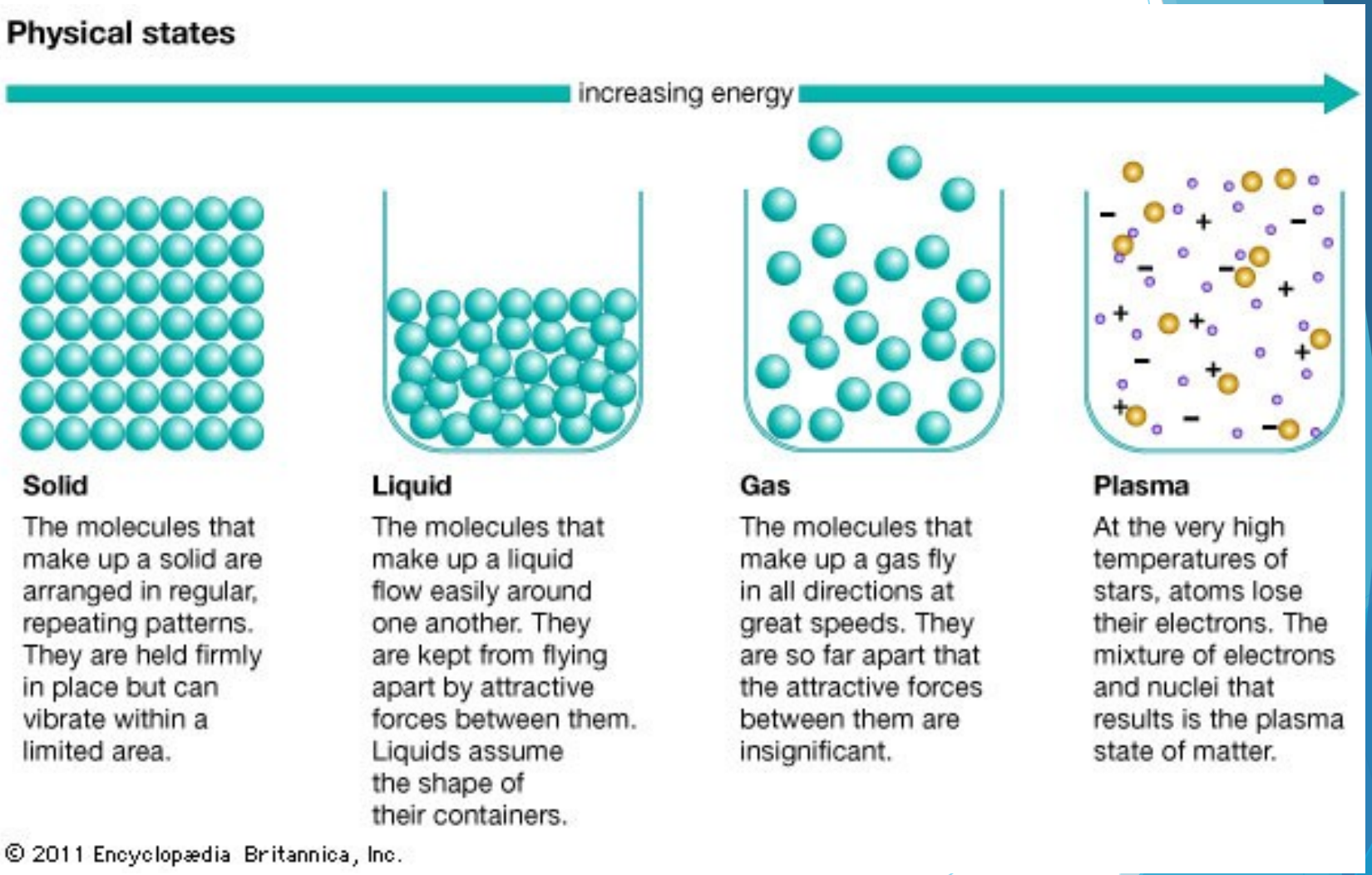
Chart of the Nuclides Isotope Illustration



ANS Interactive Isotopes App

https://isotopes.ans.org/

States of Matter


Physical states
increasing energy
Solid
The molecules that make up a solid are arranged in regular, repeating patterns. They are held firmly in place but can vibrate within a limited area.
Liquid
The molecules that make up a liquid flow easily around one another. They are kept from flying apart by attractive forces between them. Liquids assume the shape of their containers.
Gas
The molecules that make up a gas fly in all directions at great speeds. They are so far apart that the attractive forces between them are insignificant.
Plasma
At the very high temperatures of stars, atoms lose their electrons. The mixture of electrons and nuclei that results is the plasma state of matter.
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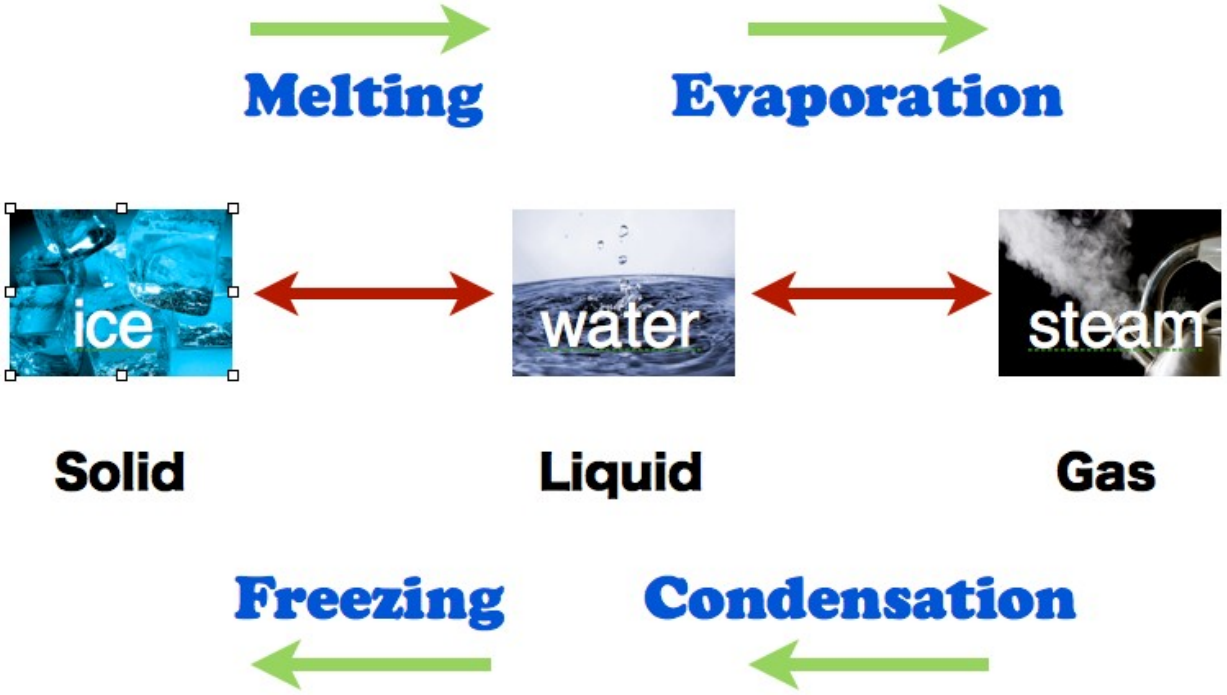
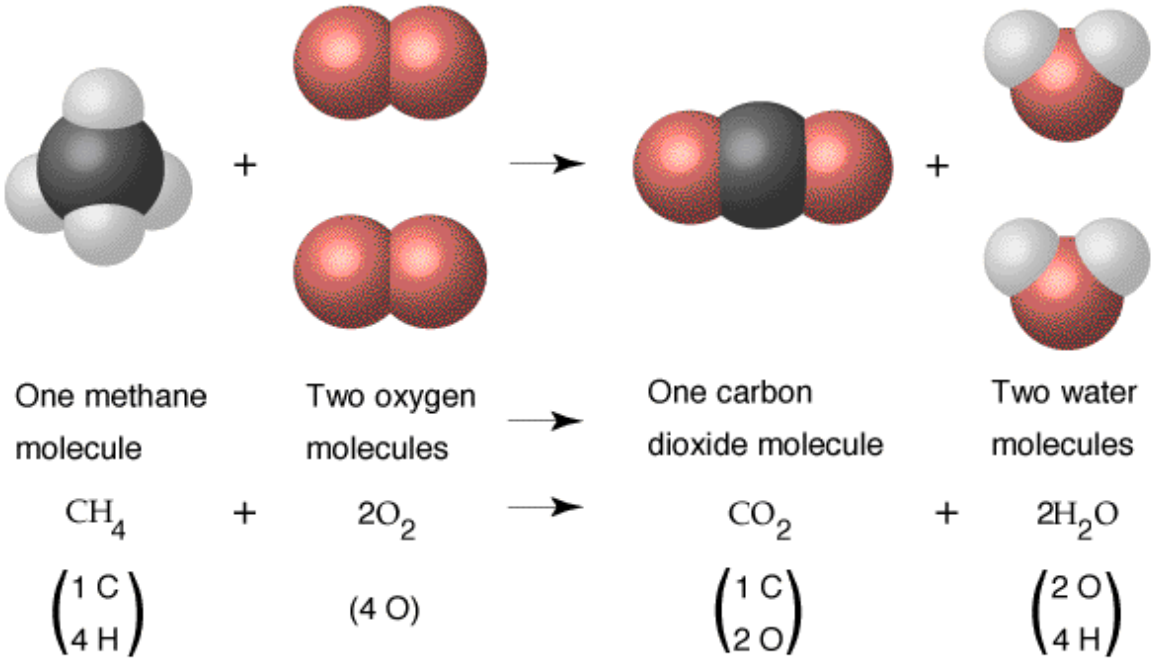
Physical Changes in Matter

Changes of state – involve changes in internal energy of atoms



Chemical Changes in Matter

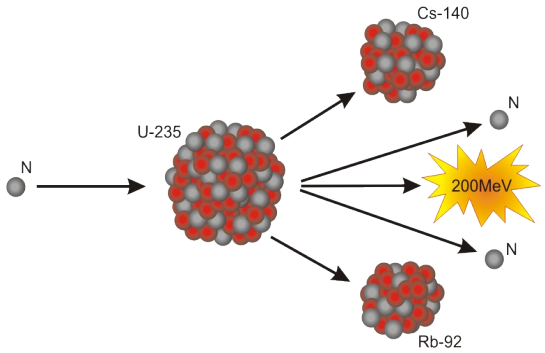
Chemical reactions – involve interactions of electrons in atoms

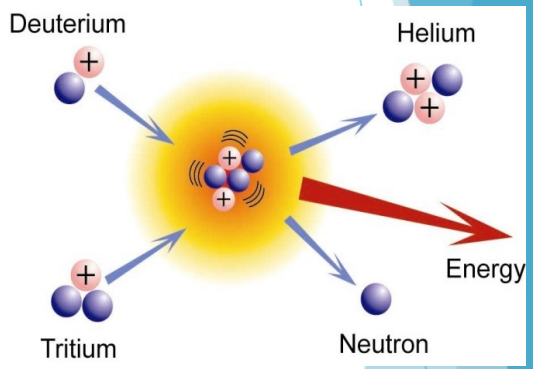


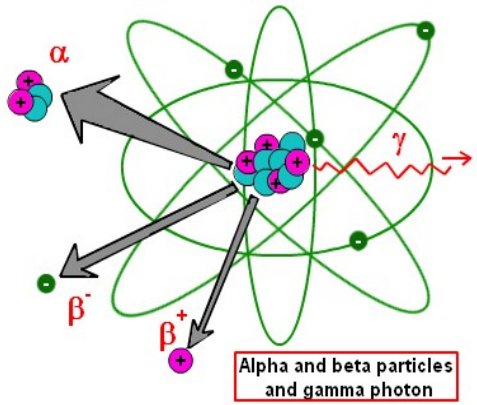
Combustion of CH_4 produces about 0.0035 eV per gram CH_4

Nuclear Changes in Matter

Nuclear changes – involve changes in nuclei of atoms (fission, fusion, radioactive decay)



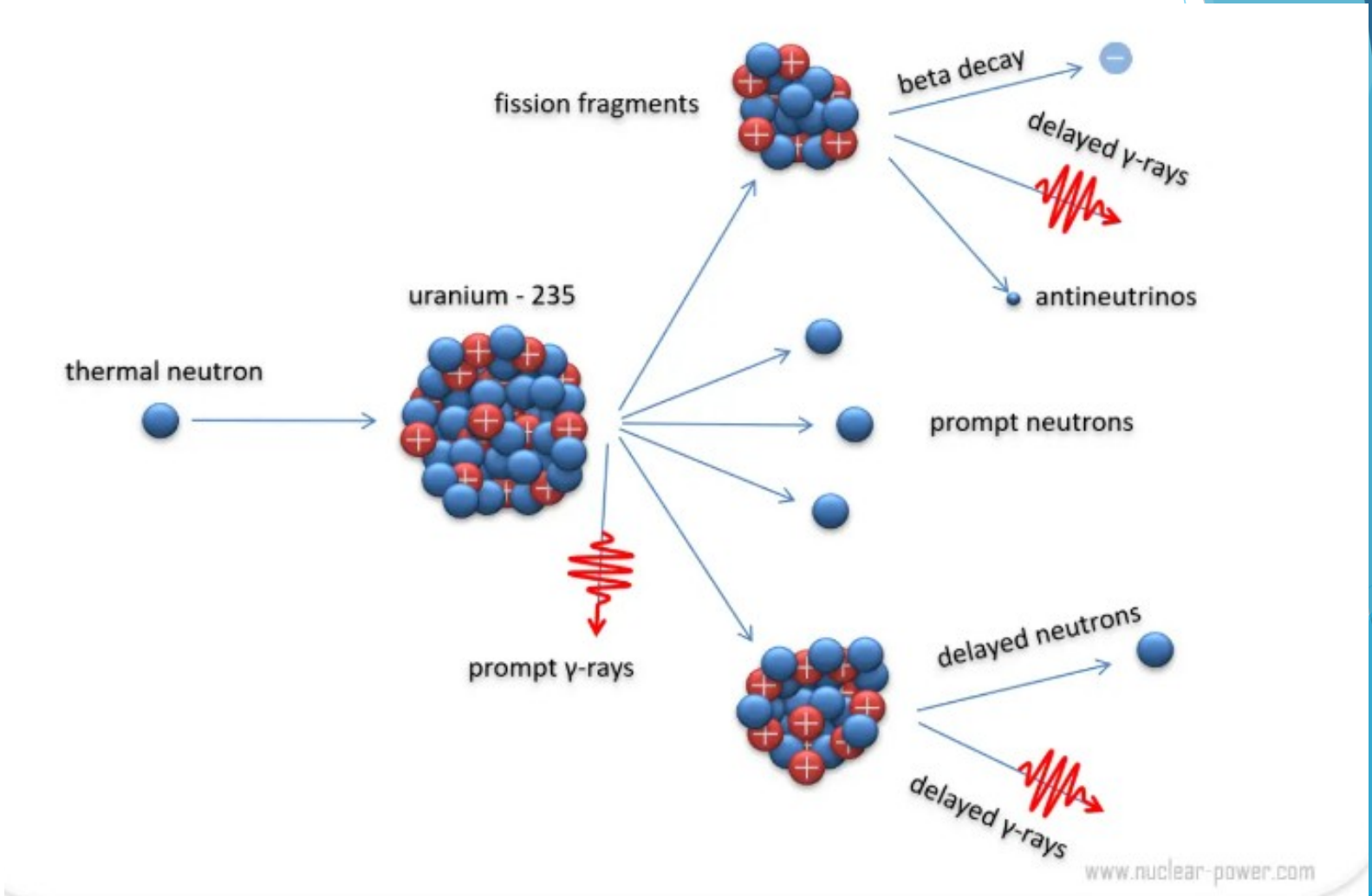




Fission

Splitting the Atom

Fission Illustrated



U-235 Fission Fragment Distribution

Fission Energy Disposition

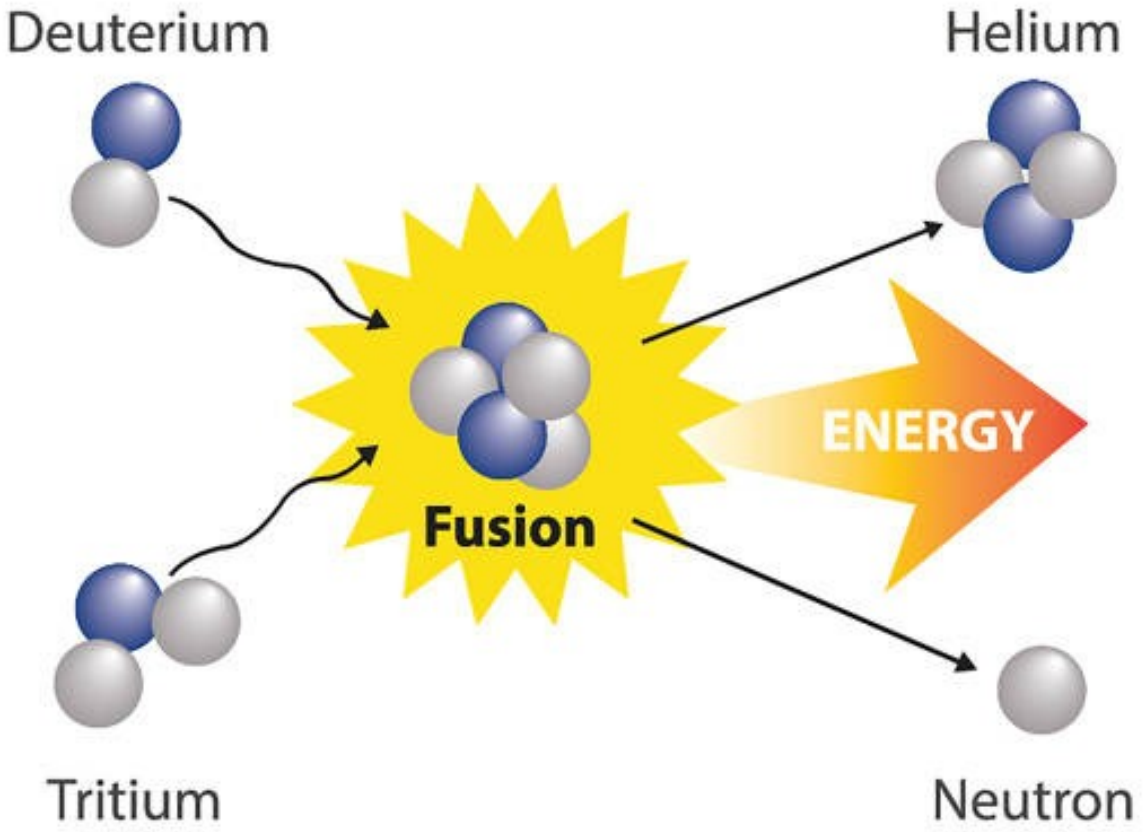
	MeV	%
Fission Fragment Kinetic Energy	168	84
Fission Neutron Kinetic Energy	5	2.5
Prompt Gamma-ray Energy	7	3.5
Fission Fragment Delayed Radiation		
Beta Particle Energy	8	4
Gamma-ray Energy	7	3.5
Radiative Capture Gamma-ray Energy	5	2.5
Total	200	100

Kinetic energy and radiation energy is converted to thermal energy in reactor materials.

Fusion

Harnessing the Sun

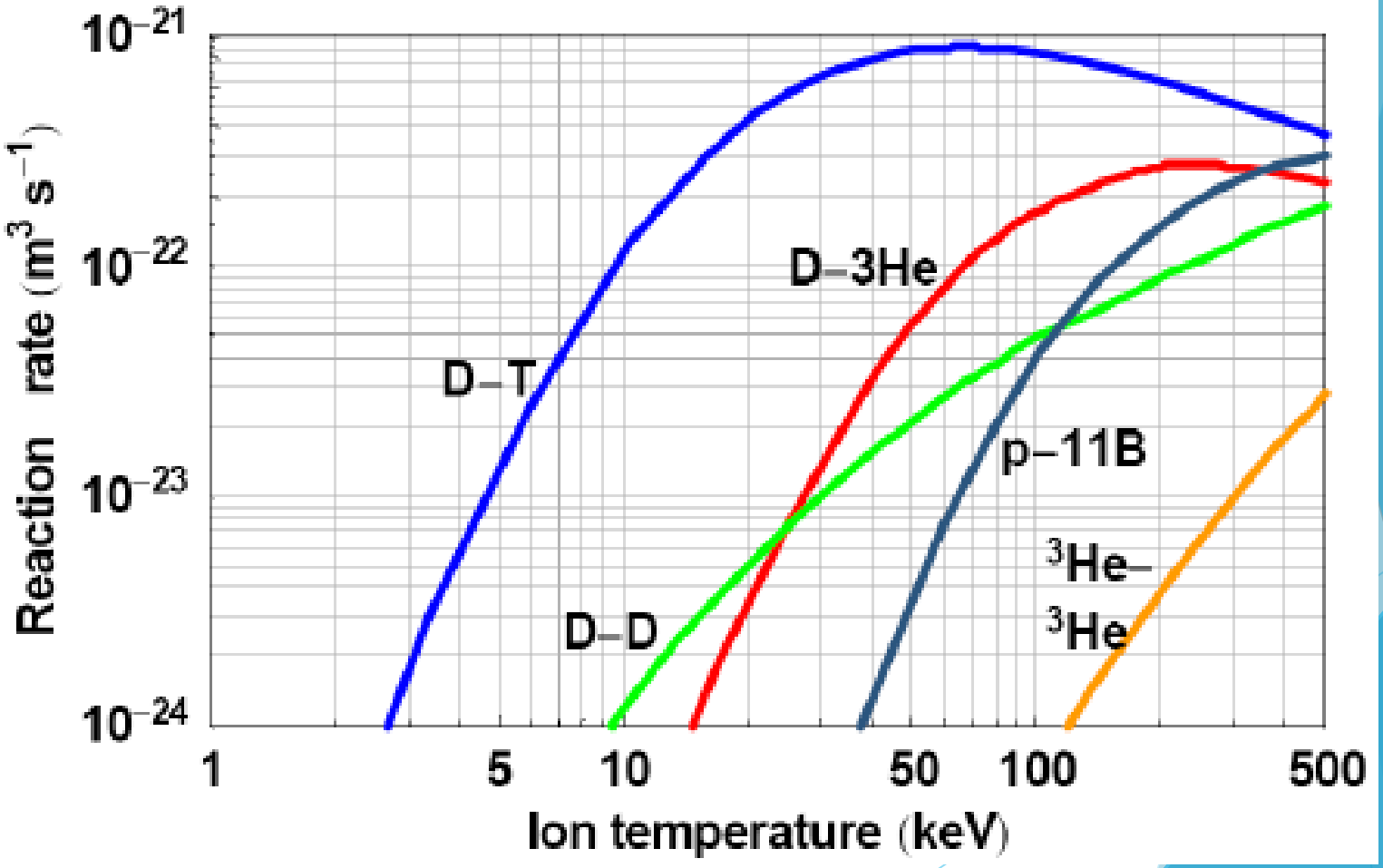
Fusion Illustrated



Potentially Useful Fusion Reactions

Reaction	Shorthand notation	Reaction energy (MeV)	Threshold plasma temperature (keV)	Maximum energy gain per fusion
${}_1^2\mathrm{D} + {}_1^3\mathrm{T} \rightarrow {}_2^4\mathrm{He} + {}_0^1\mathrm{n}$	D-T	17.6	10	1800
${}_1^2\mathrm{D} + {}_1^2\mathrm{D} \rightarrow {}_2^3\mathrm{He} + {}_0^1\mathrm{n}$	D-D	3.2	50	70
${}_1^2\mathrm{D} + {}_1^2\mathrm{D} \rightarrow {}_1^3\mathrm{T} + {}_1^1p$	D-D	4.0	50	80
${}_1^2\mathrm{D} + {}_2^3\mathrm{He} \rightarrow {}_2^4\mathrm{He} + {}_1^1p$	D-^{3}He	18.3	100	180
${}_5^{11}\mathrm{B} + {}_1^1p \rightarrow 3\,{}_2^4\mathrm{He}$	p-^{11}B	8.7	300	30

Fusion Reaction Rate vs Plasma Temperature



D-T Fusion Energy Disposition

	MeV	%
He-4 Kinetic Energy	3.5	20
Neutron Kinetic Energy	14.1	80
Total	17.6	100

D-T fusion produces about 20 MeV per gram of D-T.

Ideally, the He-4 nuclei (alpha particles) would expend
their energy heating the D-T plasma.

Neutron kinetic energy would be converted to thermal energy in reactor materials.

Radioactive Decay

Transmutation of Atoms

Radioactive Decay

The process by which an unstable atomic nucleus becomes more stable by emitting energy in the form of particles (alpha and beta), oftentimes with accompanying ionizing electromagnetic waves (gamma-rays)

Types of Radioactive Decay

- Alpha (α) Decay
  - Helium nucleus (2 protons & 2 neutrons)
- Beta Minus (β^-) Decay
  - Electron emitted from atomic nucleus when a neutron converts to a proton and an electron
- Beta Plus (β^+) Decay
  - Positron (antimatter counterpart of electron) emitted from atomic nucleus when a proton converts to a neutron and a positron
- Electron Capture (ε)
  - Proton in nucleus combines with captured inner shell electron of atom to produce a neutron

Radioactive Decay Terminology

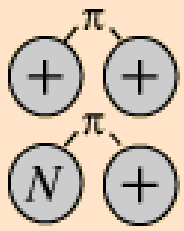
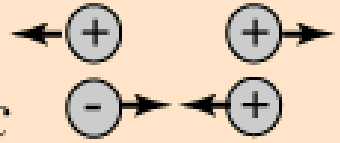
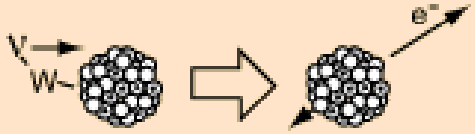
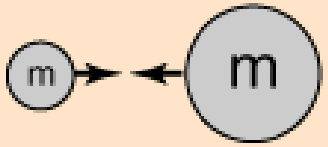
- Original nucleus called parent nucleus
- Nucleus resulting from radioactive decay called daughter nucleus
- Radioactive decay transmutes (changes) original atomic element (parent) into different atomic element (daughter)
  - Daughter nucleus has different number of protons than parent nucleus and is therefore different element

Fission and Fusion Radioactive Byproducts

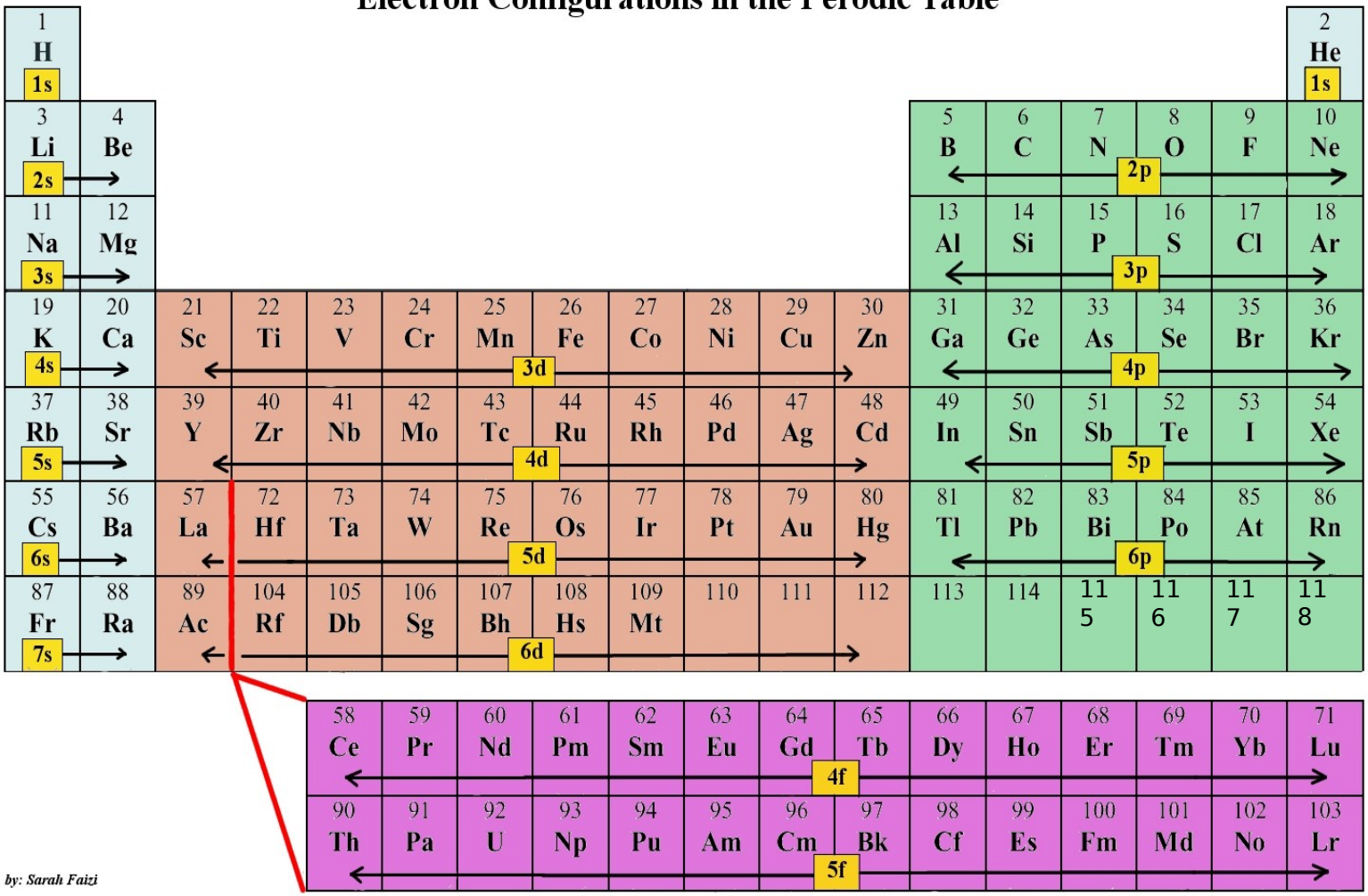
- Fission fragments and many decay daughter isotopes are radioactive
- Absorption of very energetic fusion neutrons in fusion component/system materials creates radioactive isotopes
- Primary decay modes for fission and fusion radioactive byproducts are beta minus, beta plus, and electron capture

Supplemental Slides

Fundamental Forces

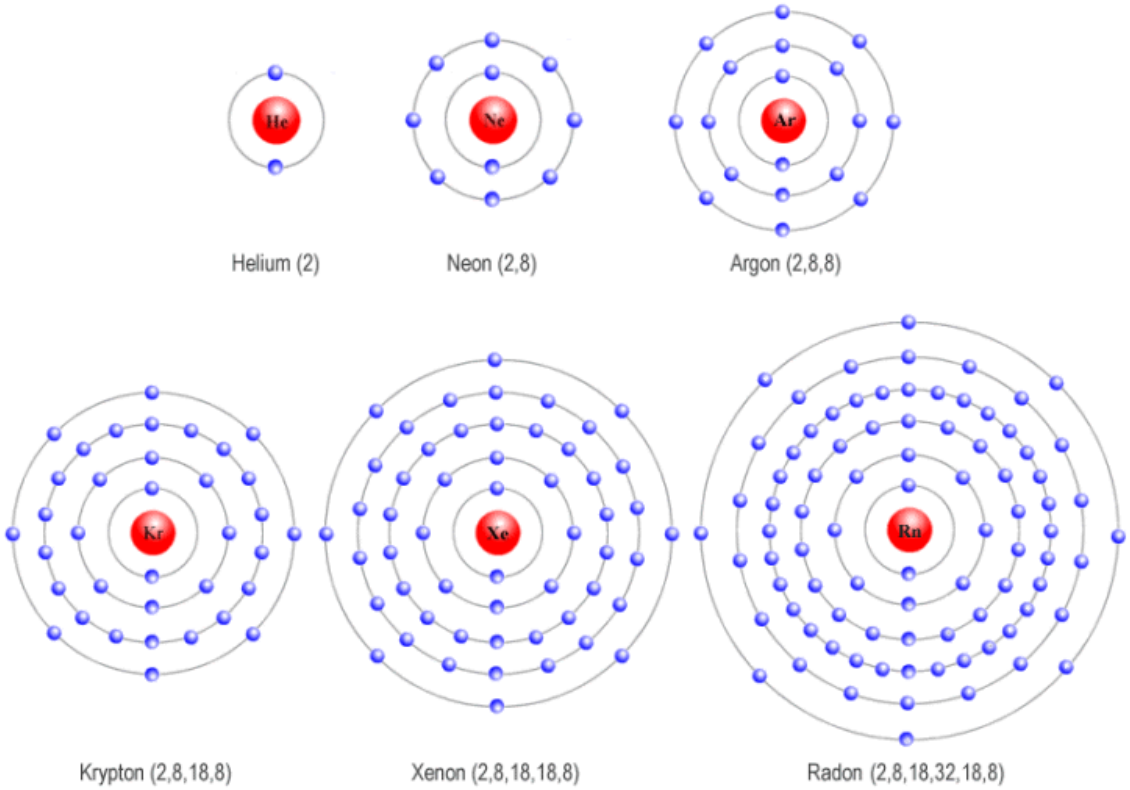
		Strength	Range (m)	Particle
Strong	 Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	 neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

Electron Configurations in the Perodic Table

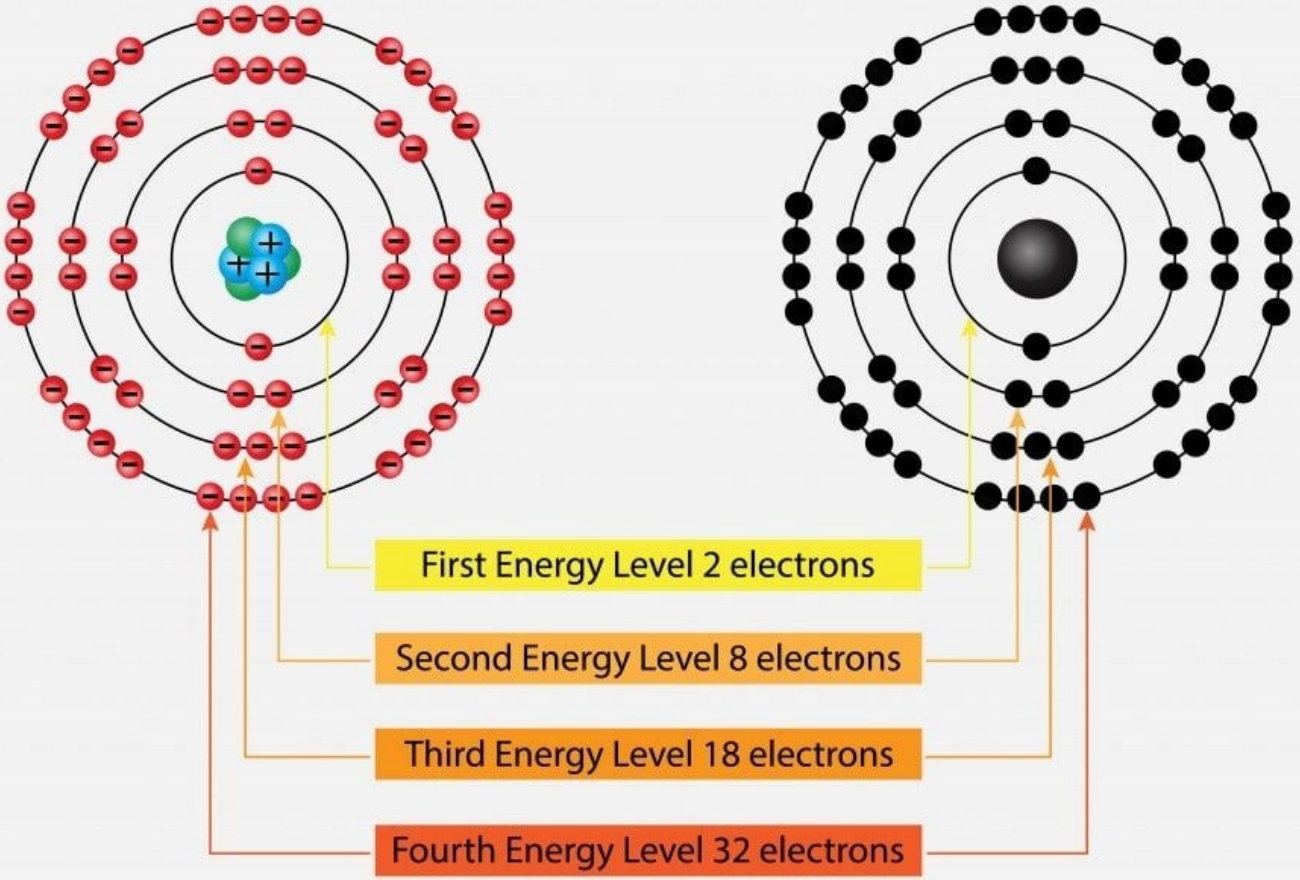


by: Sarah Faizi

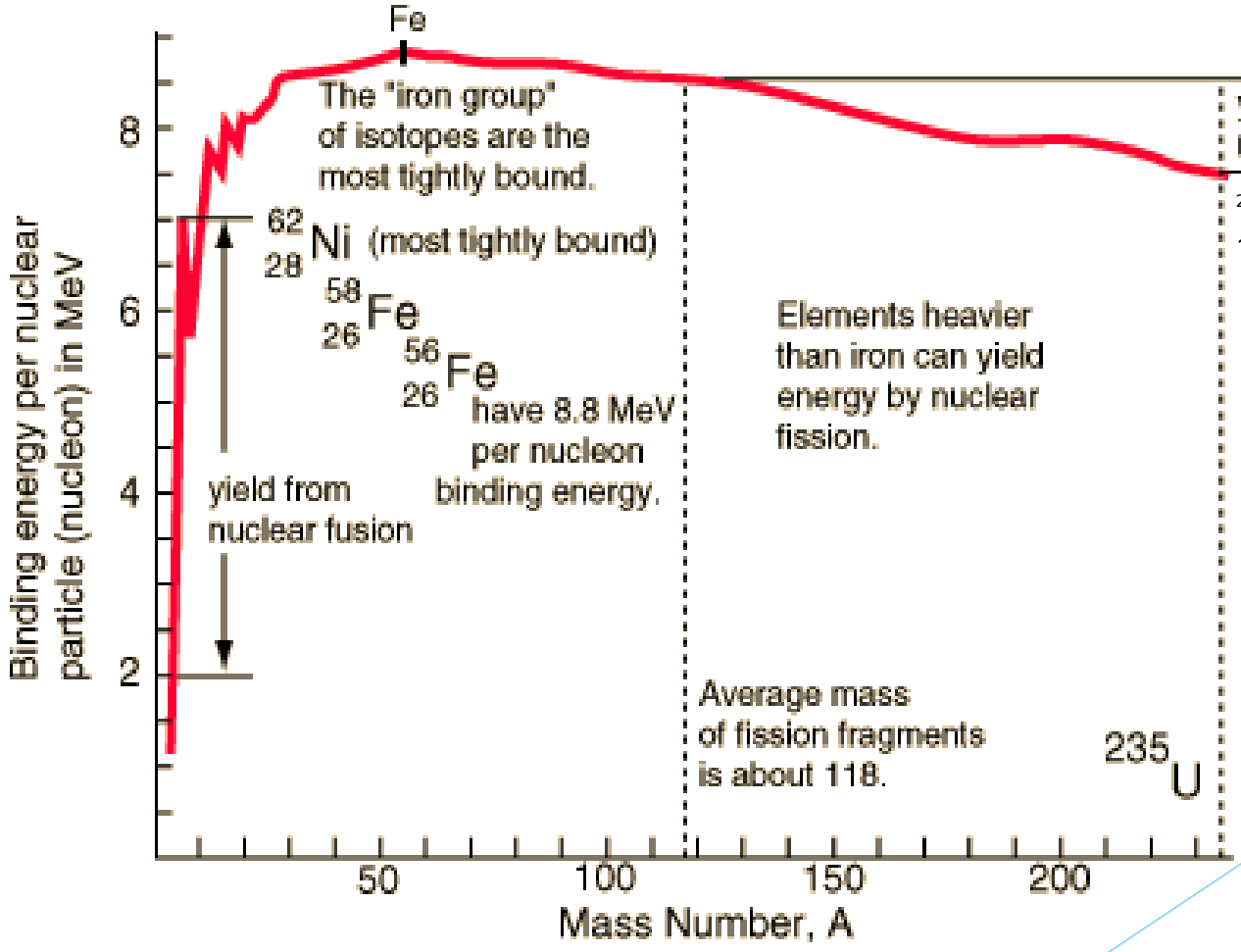
Noble Gas Electron Shell Illustrations



Electron Shell Diagram


First Energy Level 2 electrons
Second Energy Level 8 electrons
Third Energy Level 18 electrons
Fourth Energy Level 32 electrons

Binding Energy per Nucleon



Chemical vs Nuclear Reactions

CHEMICAL REACTIONS

- Occur when bonds are broken and formed
- Involve only valence electrons
- Associated with small energy changes
- Atoms keep the same identity
- Temperature, pressure and concentration all affect the rates of reactions

NUCLEAR REACTIONS

- Occur when nuclei combine, split and emit radiation
- Can involve protons, neutrons and electrons
- Associated with large energy changes
- Atoms of one element are often converted into atoms of another element
- Temperature and pressure do not normally affect the rates of reactions